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INTENSITY OF SOLAR RADIATION AT THE SURFACE OF THE EARTH, AND ITS VARIATIONS WITH LATITUDE, ALTITUDE, SEASON, AND TIME OF DAY[1]

By HERBERT H. KIMBALL, Research Associate

[Blue Hill Observatory, Milton, Mass., December 1934]

A paper under the above title was prepared by I. F. Hand, of the United States Weather Bureau, and myself at the request of the subcommittee on survey, committee on radiation, division of biology and agriculture, National Research Council, for publication in a monograph on "The effect of radiation on living organisms." With the consent of the committee, the paper was given before the American Meteorological Society at the December 1934 meeting, in Pittsburgh, in an abbreviated form, of which the following is a summary:

The principal causes of variation in both the intensity and quality of solar radiation are as follows:

(1) Scattering by the gas molecules of the atmosphere.

(2) Scattering by the dust and other impurities in the atmosphere. The depletion by both this and the preceding cause is at a maximum in the ultra-violet, and diminishes toward the infra-red or long-wave end of the spectrum.

(3) Absorption by atmospheric gases, principally by water vapor in well-marked bands in the infra-red, and by ozone in the ultra-violet.

The following causes affect principally the intensity of solar radiation as received by the earth.

(4) The distance of the earth from the sun, which is at its maximum early in July, minimum early in January, and mean in early April and early October. As a result, with similar atmospheric conditions, and the same solar zenith distance, intensities early in January should exceed those in early July by 7 percent.

(5) Variations in the value of the solar constant, which variations are insignificant in comparison with (1) to (4), enumerated above.

If we multiply the atmospheric transmission coefficients given by the curved lines of Figure 1 by 1.94, the value of the solar constant of radiation, we obtain the corresponding solar radiation intensities. Thus, for Washington, D. C., in June, with the sun 60° from the zenith, air mass 2, the average transmission is 0.474, and the radiation intensity is 0.92 gr. cal./min./cm^2.

Figure 1 shows the highest radiation intensity ever measured to be 1.84 gr. cal./min./cm^2; it was obtained by means of a pyrheliometer attached to a balloon which carried the instrument to a height of 22,000 meters. The second highest intensity was also obtained by means of a pyrheliometer attached to a balloon and carried to a height of 7,500 meters, where an intensity of 1.80 gr. cal./min./cm^2 was obtained. A group of stations on mountains ranging in height from 3,500 to 4,500 meters give intensities of about 1.75 gr. cal./min./cm^2. These intensities have all been extrapolated to what they would have been with the sun in the zenith, and with the earth at its mean solar distance.

Coming down to lower level stations, we obtain for Lincoln, Nebr., an intensity of 1.53 in February, and 1.32 in August; while for Washington, D. C., altitude 127 meters, the intensity for February is 1.45, and for June, 1.24; all in gram calories per minute per square centimeter of surface normal to the incident radiation.

The depression of the summer intensities at Lincoln and Washington as compared with the winter intensities, when reduced to mean solar distance and to intensity for the sun in the zenith, show the seasonal variation in solar radiation intensities at these two stations. This depression is shown for other stations through the comparison of mean noon values actually observed, as follows:

Santa Fe, N. Mex., August, 1.43; December, 1.52; Washington, D. C., 1.19, for both August and December, the lowest averages for noon for any months; Blue Hill, Mass., 1.25, also for August and December, with no lower average in any other month; Madison, Wis., 1.28 in August, with 1.24 in October, and 1.29 in September and December. Madison, however is the farthest north of the pyrheliometric stations in the United States, and the latitude effect is more noticeable here in the winter months than at stations in lower latitudes.

Within the Arctic Circle, in midwinter, the solar radiation is, of course, zero. With the return of spring, however, high intensities prevail. Thus, at Mount Evans, on the Greenland ice cap, latitude 66°51′ N, altitude 363 meters, in April, with solar zenith distance 60° and 70.7°, respectively, the measured mean solar radiation intensities were 1.45 and 1.28 gr. cal./min./cm^2, which are substantially the intensities measured at Davos, Switz., lat. 46°48′ N, altitude 1,561 meters; again, at Treurenberg, Spitsbergen, latitude 79°55′ N, altitude 3 meters, in May, June, and July, with the sun 70.7° from the zenith, the average measured intensity was 1.33 gr. cal./min./cm^2, the same as the intensities measured on Mount Wilson, Calif., about a mile above sea level, with the sun at this same distance from the zenith.

[1] Substantial assistance from the geophysical research fund of the Blue Hill Observatory in the preparation of this summary is gratefully acknowledged.

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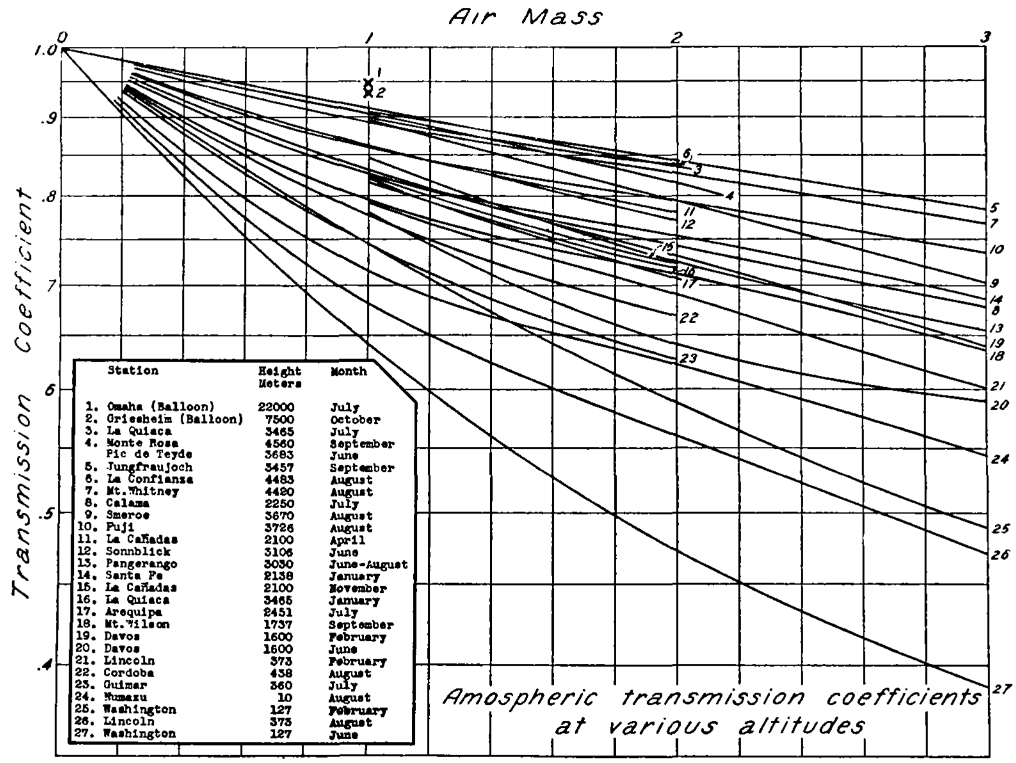

FIGURE 1.—Atmospheric transmission coefficient different altitudes.

The following are representative low-level stations within the tropics, and their radiation values:

Stations	Latitude	Longitude	Altitude, meters	Solar zenith distance	Radiation intensity	Month
	° ′	° ′		°		
Flint Island	10 05 S	152 10 W		60	1.29	Dec.
Apia, Samoa	13 48 S	171 46 W	2	60	1.10	Nov.-Feb.
Do				60	0.98	Mar.-Oct.
Bangkok, Siam	13 44 N	100 30 E	10	5	1.22	May.
Batavia, Java	6 11 S	106 50 E	8	60	1.13	Jan.-Feb.
Do				60	0.85	Aug.-Oct.

The following table of intensity readings obtained at Washington, D. C., on the afternoon of November 9, 1909, with an Ångström pyrheliometer, shows the variations in intensity as the sun approaches the horizon.

Solar zenith distance	60.0	75.7	80.7	83.2	84.7	85.8	86.9	87.6	88.2	88.7	89.2
Air mass	2.0	4.0	6.0	8.00	10.0	12.0	15.0	18.0	21.0	25.0	29.0
Intensity; gr. cal	1.230	0.999	0.804	0.653	0.531	0.454	0.365	0.292	0.236	0.176	0.131

Unit air mass is defined as the length of the vertical path through the atmosphere. The path is twice as long (m=2) 60° from the zenith, and 25 times as long 88.7° from the zenith, or 1.3° above the horizon. The solar intensity for air mass 2 was only slightly above the average for November. Therefore, we may say that the intensity for zenith distance of the sun 89.2°, or altitude above the horizon 0.8°, approximates closely to the intensity just before the lower limb of the sun touches the horizon.

The vertical component of the total solar radiation (direct+diffuse) received at the surface of the earth.—About half the radiation lost from the incoming rays through scattering, as already described, is finally received at the surface of the earth as diffuse radiation. This, added to the vertical component of the direct solar rays, makes up the total radiation received at the surface of the earth. Figure 2 gives annual curves of daily totals of radiation.

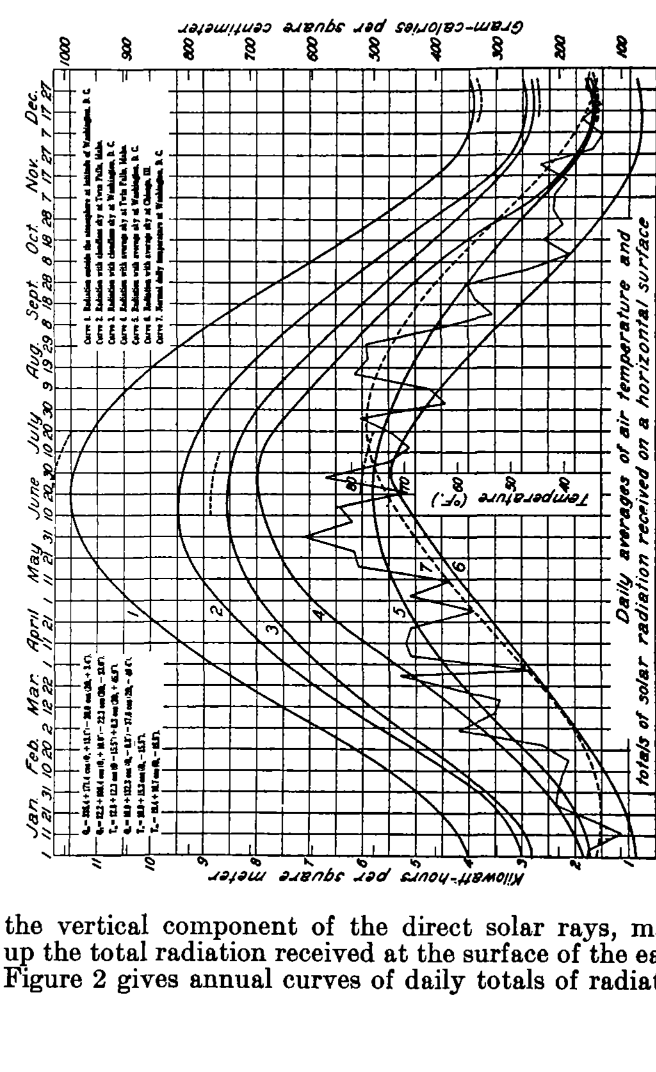

FIGURE 2.—Annual curves of daily totals of radiation.

Curve 1 is for just outside the atmosphere at the latitude of Washington, and is simply the vertical component of the direct solar radiation, or the vertical component of the solar constant corrected for the distance of the earth from the sun. Curves 2 and 3 give daily totals of the average radiation, including the diffuse, received on cloudless days at Twin Falls, Idaho, latitude 42°29′ N, altitude 1,310 meters, and at Washington, D. C., latitude 38°56′ N, altitude 30 meters; while curves 4 and 5 give these radiation data for the average of all days, at the respective stations. On the normal values of curve 5 are superposed the weekly averages for Washington for the year 1925, to show the rapid fluctuations in radiation receipt from week to week.

In curve 6 are given weekly averages for Chicago, Ill., latitude 41°37′, altitude 210 meters. The annual totals received at the three smoky cities, Chicago, Pittsburgh, and New York, are about 100,000 gr. cal./min./cm², which is approximately one-fourth less than is received at Washington, D. C., and Blue Hill, Mass., both of which have relatively clear atmospheres (the latter is also on nearly the same latitude as the three cities first named), and one-third less than is received at stations like Riverside and Fresno, Calif., and Twin Falls, Idaho.

For the maximum average daily total radiation, we have from figure 2, curves 4 and 5, for Twin Falls and Washington, respectively, 689 and 500 gr. cal./cm². Outside the United States, for Johannesburg, South Africa, 606 gr. cal. in November; Habana, Cuba, 658 gr. cal., in July; Fairbanks, Alaska, just outside the Arctic Circle, 583 gr. cal. in June; at Abisko, Sweden, just within the Arctic Circle, 468 in June; at Green Harbor, latitude 78° N., 546 in June; and at Sveanor, Spitzbergen, latitude 80° N., for the 22 days from June 10 to July 1, inclusive, the average daily radiation received was 580 gr. cal.

For the mid-day hourly amount in June we have the following, in gr. cal.: For Miami, Fla., 66.8; Washington, D. C., 66.8; Lincoln, Nebr., 64.4; Twin Falls, Idaho, 77.4; Fresno, Calif., 83.6; Fairbanks, Alaska, 59.6. It thus appears that while in the Arctic regions the intensity of solar radiation at normal incidence, and the total daily amounts in mid-summer, compare favorably with like data for stations at lower latitudes, and especially with tropical stations, nevertheless the mid-day hourly amounts received on a horizontal surface are much less, on account of the comparatively low altitude of the sun at this time.

Variations in the quality of solar radiation.—At Washington, D. C., and at the Blue Hill Observatory, Milton, Mass., the intensity of the radiation has been measured by means of glass color screens that cut out all radiation of wave lengths below a certain point in the spectrum that is quite accurately known, but which may be shifted slightly by changes in the temperature of the screens (which are necessarily exposed to the sun outside the observatory). The effect of this temperature change is a subject that is scheduled for investigation.

An abundance of screened solar radiation measurements are available from both European and American observatories, but time has permitted the examination of only a small fragment of the data in quite a preliminary manner.

The sections of the spectrum measured are as follows: (Consult, fig. 3.) (1), the total spectrum; (2), all above 0.636μ, or the red and infra-red, here for brevity designated "red"; (3), all above 0.526μ. In addition to (2), the red band, (1) minus (3), gives a measure of the intensity in that part of the spectrum below 0.526μ, or in the blue-violet, for brevity here designated "blue"; while (3) minus (2), or between 0.526μ and 636μ, which includes most of the so-called visible spectrum, is here designated "visible."

The measurements from three typical stations, including Zugspitze, Germany, lat. 47°25′ N., long. 10°59′ E., altitude 2,962 meters, may be summarized as follows:

ZUGSPITZE, GERMANY

Season of year	Air mass	Percentage of total in each		
		Red	Blue	Visible
Winter	3.82	68.6	18.8	12.8
Year	2.90	67.7	19.3	12.9
Spring	2.37	65.7	21.1	13.1
March–August	2.00	63.1	22.9	14.1
April–August	1.53	62.2	24.1	13.6
June–August	1.14	61.1	25.0	13.9
BLUE HILL, MASS.				
Winter	3.47	72.3	13.4	14.1
Summer	3.26	67.1	16.0	16.9
January–October	2.30	68.0	16.3	15.7
November–December	2.51	69.8	14.8	15.4
June	1.25	62.8	20.6	16.6
WASHINGTON, D. C.				
January–December	3.61	70.8	14.1	14.9
Do	2.35	68.8	16.1	15.0
February–April	1.56	65.7	19.9	14.3

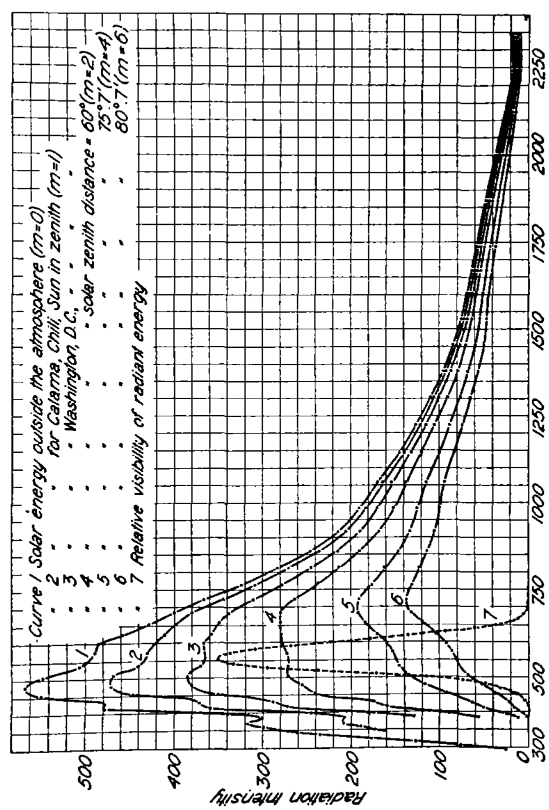

FIGURE 3.—Normal solar radiation energy-curves.

The following relations are to be noted:

(1) An increase in the percentage of the blue content of the solar spectrum occurs with decrease in air mass, as we should expect, since the depletion by scattering in that part of the spectrum is much greater than in the longer wave-length sections.

(2) A decrease in the percentage of the red content of the solar spectrum occurs with decrease in air mass, which

is probably a seasonal effect, since depletion in the long-wave end of the spectrum is largely due to absorption by water vapor, and water vapor is much more abundant in the atmosphere during the warm than during the cold season of the year.

(3) Variations in the visible part of the spectrum, while small, indicate about the same increase in the percentage content of visible radiation in the solar spectrum with decrease in air mass as is indicated by table 3, p. 479, MONTHLY WEATHER REVIEW for October, 1924 "Illumination equivalents of a gram-calory/min./cm^2 of radiation, with the sun at different zenith distances." The increase there shown from zenith distance 75.7 (m=4.0) to zenith distance 25° (m=1.1) is 9 percent, which is the same as is shown for Zugspitze, above.

While existing solar radiation measurements in the Tropics are inadequate to give a complete picture of its characteristics, the data here presented do not substantiate the claims frequently made as to its excessive intensity as compared with that in temperate zones. The annual total received on a horizontal surface at Habana, Cuba, for example, is about the same as that received at Lincoln, Nebr., and considerably less than that received at stations in the States of California and Idaho; while the maximum hourly amount received at Miami, Fla., is considerably less than that received at most stations in central latitudes of the United States.

ROUTINE DAILY PREPARATION AND USE OF ATMOSPHERIC CROSS SECTIONS

By HURD C. WILLETT

[Massachusetts Institute of Technology, Cambridge, Mass.]

The greatly increased number of daily meteorological soundings through the lower troposphere by airplane which are now at the disposal of the American weather forecaster makes necessary the development of a system for the representation of these valuable data, in the most useful and comprehensive form which limited time will allow. Any complete three-dimensional representation of the fields of the meteorological elements is likely to remain too complicated a procedure for use in daily weather forecasting, and as yet our data from upper levels are far from sufficient for such a representation. However, some method of presenting a unified picture of atmospheric conditions in the vertical, corresponding to our two dimensional analysis of the surface data, is urgently needed, to supplement the present practice of representing the separate aerological soundings individually on one of the standard forms of diagrams. To obtain such a representation we have come to rely increasingly in our meteorological work at the Massachusetts Institute of Technology, on so-called "atmospheric cross sections." For such a cross section we choose a line, along which there lies a maximum number of airplane stations, as the base line, i. e., the line of intersection of the vertical plane with the ground surface. The data obtained from the airplane ascents are then plotted on the vertical cross-section sheet, the ordinates representing elevation, so that the frontal discontinuities may be drawn in. Subsequently isopleths of temperature, specific humidity, or any meteorological elements desired, may be sketched. Thus we get a two-dimensional picture, along a vertical plane containing a maximum number of observations, of the air mass and frontal structure of the atmosphere, and of the horizontal air movement. From the horizontal air movement, and the frontal slopes, we may draw conclusions about vertical velocities also.

During the past year I have worked up a large number of such atmospheric cross sections for short periods of special interest within the last 3 years, or when the data were more than usually complete. The results of this work proved to be of such interest and so illuminating that I decided at the end of last summer to try to work out some routine practice by which at least a part of the present extensive network of stations making daily airplane soundings might be utilized in the regular daily preparation of certain standard cross sections. For this purpose 3 groups of stations were chosen, 2 of these groups constituting rather straight north-south sections, and 1 long east-west section along a broken line. In the more easterly north-south section are Detroit, Dayton, Nashville, Montgomery, and Pensacola; in the more westerly one, Fargo, Omaha, Oklahoma, and San Antonio. In the long broken east-west section we have Boston, New York, Washington, Dayton, St. Louis, Omaha, Cheyenne, Billings, Spokane, and Seattle. On our cross-section sheets the ordinates give elevations (scale 1 inch to 1 kilometer), and the abscissae are horizontal distances (same scale as the M. I. T. weather maps). The base line represents roughly the topographical contour, on the given scale of elevation, of the ground surface along each section. Vertical lines at the point of each station serve to facilitate the plotting of the data in the vertical.

Lack of time usually prevents the daily plotting of all three cross sections. Usually it is the aim to complete the east-west section every day, and the north-south sections only in cases of particular interest. There are occasions when, owing to more complete data or to the particular meteorological situation, the completion of one or both of the north-south sections may be preferred to that of the east-west section. The plotting procedure is quite simple. The desired stations are selected from the morning reports, and for each reported level the potential temperature and specific humidity are obtained graphically. Then at the respective elevations (points on the vertical line representing each station) the potential temperature and specific humidity are entered at the right, the actual temperature at the left. Where we have pilot-balloon observations, the wind direction and velocity (Beaufort) are also represented by barbed arrows, the direction parallel to the base line representing the direction of the baseline itself. Thus on a west-east section a wind arrow flying to the right and parallel to the base represents a west wind, on a north-south section, a north wind.

As soon as the data are entered, we are ready to carry out the analysis, or the location and designation of the fronts and air masses. This is not always easy to do, and requires considerable experience. It is best carried out in conjunction with the analysis of the surface map, but unfortunately the delay so frequently experienced in the receipt of some of the aerological data usually makes this impossible. Both the surface analysis and the cross-section analysis mutually benefit from such a joint consideration, but usually the surface analysis cannot be delayed until all the aerological observations are in, and of course the cross section analysis should be attempted only with the greatest possible amount of material plotted on the cross section. When the loca-